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13. ABSTRACT (Maximum 200 words)

We have developed the basic science underlying active quasi-optics. We have investigated power handling, noise, stability, efficiency and reliability, and developed the CAD tools necessary for industrial applications. In addition, we have demonstrated a single-chip output power of 5 W in the millimeter-wave frequency range, and developed practical waveguide packaging techniques for the devices. In the lower microwave frequency range we have developed a coaxial fin-line combiner that gives an output power of 50W with a 3:1 bandwidth. These demonstrations, together with the design techniques we have developed, should allow industry to solve the critical problems of multi-watt level solid-state power sources for millimeter waves, and broad-band high-power sources at lower microwave frequencies.

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Caltech Quasi-Optic MURI Final Progress Report

Forward

We are appreciative of the Army Research Office contract monitors who have enthusiastically supported quasi-optics technology. The work was first initiated by Jim Mink twenty years ago. The contract monitor for the MURI in the early years was Jim Harvey, and in the later years, Dev Palmer. These contract monitors have set a very high standard for technical leadership, and Jim Mink and Jim Harvey have both been recognized as Fellows of the IEEE. In addition, we would like to thank Elliott Brown for his strong support of quasi-optics when he was a DARPA program manager. We also appreciate the interest and advice from the members of the MURI Scientific Board.

The Caltech quasi-optic power-combining MURI included five research groups at four universities: Dave Rutledge at Caltech, Zoya Popovic at the University of Colorado, Robert York and Mark Rodwell at the University of California at Santa Barbara, and Mike DeLisio at the University of Hawaii. In all, 27 graduate students and visiting researchers were supported. The International Microwave Symposium has devoted one or two sessions each year to this topic, and the sessions have been dominated by the members of the Caltech MURI. The program supported cooperative work with Hughes Research Laboratories (Mehran Matloubian), Lockheed-Martin (Lee Mirth), and TRW, now Northrop Grumman (Roger Tsai), in the area of gallium-arsenide and indium-phosphide integrated-circuit fabrication. In addition, we collaborated with Wilson Pearson's Quasi-Optic MURI at Clemson in the area of field mapping of active quasi-optic arrays, working with Professor John Whittaker at the University of Michigan.

During the time of the MURI grant, Zoya Popovic was selected Fellow of IEEE for contributions to the development of active antenna arrays and quasi-optical power combining techniques. She also received the Humboldt Research Award for Senior US Scientists, and the ASEE/HP Terman Award. David Rutledge received the Third Millennium Award of the IEEE.

The MURI has led to one new company, Wavestream Corporation (www.wavestreamcorp.com), in Covina, CA. Wavestream was founded in 2001. Its founders include Mike DeLisio, formerly a professor at the University of Hawaii and a participant in the MURI, Blythe Deckman, who received his PhD at Caltech, and Jim Rosenberg, formerly a Visiting Associate at Caltech. Wavestream is developing millimeter-wave single-chip quasi-optical power amplifiers based on the grid-amplifier approach invented at Caltech. This is an area where we have very much needed power sources. The existing tube amplifiers are large and extremely expensive. The reliability of the tube amplifiers is poor, and the primary supplier is in Latvia. Wavestream has gone far beyond the progress that was made in the university research groups, recently submitting a paper to the International Microwave Symposium setting a record of more than 10 watts from a single chip at 30GHz with standard waveguide inputs and outputs. This is a very promising result indeed, and it augurs well for the success of Wavestream.

Problem Studied

The field of active quasi-optics grew out of an Army Research office program started by Jim Mink in the late 1980's at Caltech. The initial idea was to investigate structures that were periodically loaded with active devices like transistors and Gunn diodes. At the time, we thought of the structures as analogous way to gas lasers. We could think of a gas laser as containing a large number of tiny amplifiers, which are excited molecules subject to stimulated emission, with spatial power combining in the output beam. Initial work emphasized oscillator grids, and a Caltech paper with then graduate student Zoya Popovic [1] won the Microwave Prize of the Microwave Theory and Techniques Society in 1991 (the references are at the end in the Bibliography).

At the same time there was a growing realization within DOD, DOE, and NASA that the problem of watt-level solid-state amplifiers for the millimeter-wave and submillimeter-wave regions was extremely difficult to solve. The issues are fundamental. The channel in a transistor has to be short to make the device fast, and this limits the voltage that can be applied. In addition, the channel width must shrink with the length to keep a reasonable impedance level for efficient coupling to an antenna or transmission line. This means that the current shrinks with the voltage. The power goes down as the frequency squared. This is why transistors that produce 1 kW are readily available in the MHz frequency range, but only a few milliwatts are available in the millimeter-wave range. People have used MMIC technology to make transmission-line Wilkinson combiners for transistors, but this also has fundamental limits. The length of the transmission lines grows linearly with the number of devices, and the losses grow exponentially. This sets a severe limit on the number of devices that can be combined before the total power actually begins to drop; typically it is about 16.

The direction of the active quasi-optics research then shifted from oscillators amplifiers. Moonil Kim demonstrated a grid amplifier in 1991 [2]. The breakthrough ideas were to use the transistors in differential pairs with balanced antenna inputs and outputs, and to use orthogonal polarizations for the input and output to stabilize against oscillations. The field broke wide open when Jeff-Liu from Caltech and Emilio Sovero from Rockwell Science Center demonstrated a monolithic 40-GHz grid amplifier in 1995 [3]. The gain for this amplifier was limited and the output power was less than a watt, but this paper gave a clear direction.

The field then received additional support from the DARPA MAFET Thrust 3 program. Elliott Brown was the program manager, and several contracts were let to industrial companies for quasi-optical power amplifiers in the 10-GHz to 100-GHz range. The results of the program were generally disappointing, with the exception of a brilliant project in Bob York's group at the University of California at Santa Barbara. They mounted MMIC amplifiers on printed circuit boards inside a hollow metal guide, and produced 160W at 10GHz [4]. The inputs and outputs were coupled to the guide by fin-line. This approach gave large powers and large bandwidths. In many ways, the approach is complementary in frequency to the Caltech grid amplifiers. York's approach appears to be best for the microwave frequencies below 30GHz, and the Caltech grid amplifiers appear to be most suitable for frequencies above 30GHz.

Even though the DARPA program was a failure in some respects, it did show that the science base for active quasi-optics was too weak to support serious commercial industrial activity, and this led Jim Harvey to propose active quasi-optics as a MURI topic. The Caltech team

proposed a program that would develop a variety of millimeter-wave power amplifiers and quasi-optical systems for the frequency range from 30GHz to 140GHz. This was aimed squarely at the critical problem of producing watt-level solid-state power sources in the millimeter-wave range. In addition, we proposed power sources for even high frequencies based on resonant tunneling diodes fabricated by JPL. When the grant was awarded, the higher-frequency work was deleted, and there was a request to thoroughly develop the science foundation for active quasi-optics.

Important Results

Grid Amplifier CAD

Much of the work on the science base for active grids has centered on the critical question of CAD. Should specially written code be used or off-the-shelf software? One approach was a specially written method-of-moments simulation developed in Michael Steer's group at North Carolina State University. The alternative approach that we followed at Caltech was to analyze a unit cell in an infinite periodic grid with Ansoft's finite-element package HFSS. The method-of-moment code gave some information about hot edges that had been seen in experiments, but could not be predicted by the unit-cell approach. However, the method-of-moment code did not predict the grid scattering parameters well, and it was abandoned. Almost all of the design work since then has used commercial finite-element software, and it follows the approach outlined by Polly Preventza in her presentation at the International Microwave Symposium in 1999 [5]. This approach has proven to quite accurate, even in current designs where the transistor size becomes a substantial fraction of the unit cell. In addition, HFSS later has proved invaluable in designing waveguide mode converters that couple TE10 waveguide input and output sections to the multi-mode region around the grid.

Other design issues have also been addressed. Jeff Liu observed a spurious non-radiating oscillation mode in some grids. He associated this with a common-mode oscillation of the differential amplifier pairs, and he developed a transmission-line model stability analysis that predicted the oscillations accurately [6]. This common-mode stability analysis has been routine in the design of all amplifier grids. It is critical in avoiding oscillations. There has also been an interest in the reliability of the grids. One of the attractive features of active quasi-optics is that it the grids degrade gracefully as transistors fail. Our analysis, confirmed by extensive follow-up measurements indicates that an x% failure rate causes a $2x$% drop in output power [7]. The noise performance of grids was investigated, and it was found for a grid amplifier, the noise temperature of the grid was the same as the noise temperature of a unit cell [8]. This is attractive, because it means that larger grids do not have more noise than smaller grids. On the other hand, larger grids do have more power-handling capacity.

This work, combined with the rapidly increasing speed of computers, and improvements in commercial CAD tools, has given a CAD environment for accurately designing grid amplifiers. However, there are fundamental limitations in the unit-cell approach, and practical restrictions in HFSS. First, it does not predict the behavior of the edges of the grid, and asymmetrical cells that couple the input and output polarizations are not modeled accurately. In this area, Mike DeLisio has done some interesting work where he considered how to minimize the generation of substrate modes in the grids [9]. Current development in quasi-optical CAD is centering on finite-difference time-domain code for the entire grid amplifier, including the waveguide mode converters.

Grid Amplifier Demonstrations

For the credibility of the active quasi-optics area, it has been critical to demonstrate real power from single chips in the millimeter-wave range. Blythe Dickman and Emilio Sovero provided the breakthrough, describing a GaAs chip with a 5-W output at 37 GHz at the 2000 International Microwave Symposium [10]. This was a record output in this frequency range for a single transistor chip at the time. This grid amplifier used 512 transistors, and had a combining loss of only 1-dB, which is far beyond the limits of conventional transmission-line combiners. Even though this result was promising, Dickman's chip was not practical except in laboratory applications, because he used extremely large plastic lenses to focus the input power onto the chip and to gather power. In the millimeter-wave frequency range, it is most convenient to use TE10 waveguide for the input and output. Lawrence Cheung used HFSS to design a mode converter that with a TE10 input that provided a uniform field across the chip. In 2001, he reported gain and power that were similar to Dickman's [11]. The following year, he made 60-GHz InP grid amplifiers with Roger Tsai at Northrop-Grumman with mode converters at the input and output, giving a convenient, compact package (Figure 1) [12]. At the high frequencies, low-transistor gain is quite limiting, but Cheung recently demonstrated a grid amplifier with a two-stage unit cell and a measured gain of 6dB at 82GHz, that should make it possible to solve this problem [13, 22].

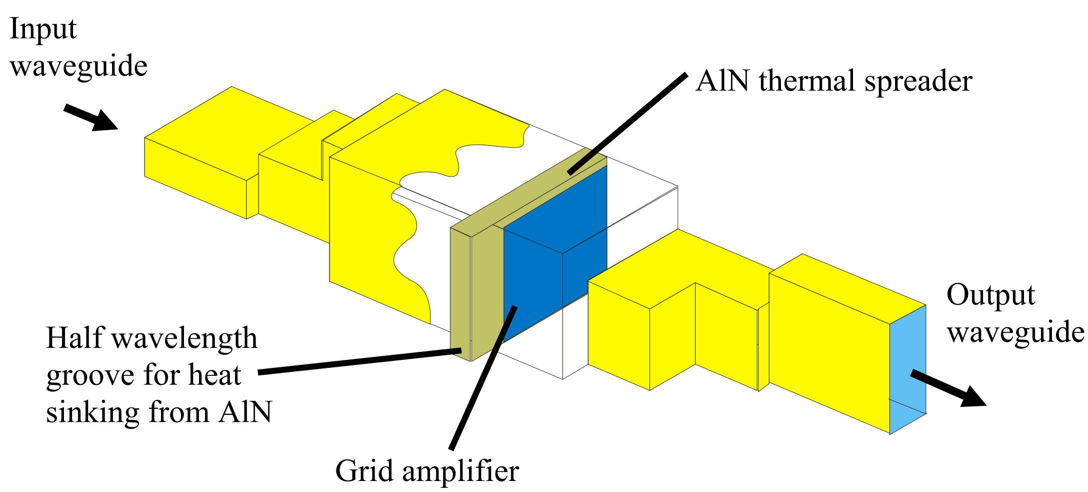


Figure 1. First fully-packaged grid amplifier with waveguide mode converters on both the input and the output sides. This amplifier had a measured gain of 2dB at 58GHz [12].

These demonstrations provided the credibility for Wavestream to raise money from venture capitalists to start the company.

Coaxial Waveguide Power Combiners

Bob York's group studied waveguide power combiners. This work followed his extremely successful MAFET 3 project which achieved output powers of over 100W in X-Band [4]. His approach uses MMIC amplifiers on finline mounted inside standard rectangular waveguide. His group developed design techniques for achieving wide bandwidths in finline, and techniques for assembling the cards in waveguide and removing excess heat [14]. It proved to be difficult to scale this technique to the millimeter-wave region, because the amplifier cards do not become small as quickly as the waveguides do [15]. A 20-GHz

rectangular amplifier gave an output of only 6W with a 2-dB combining loss. However, York's research developed in another direction. Instead of mounting the amplifier cards in rectangular waveguide, his students mounted them in circular coaxial guide. Rectangular waveguide structures are usually limited by spurious modes to about a 2:1 bandwidth, but this is much better than grid amplifiers, which typically have bandwidths of 5% or less. However, there is an opportunity for even broader bandwidths, because coaxial waveguides can have bandwidths of many octaves.

York's coaxial waveguide combiner system is shown in Figure 2 [16]. There are 32 MMIC amplifiers, and the combining loss is better than 1.5dB over the frequency range from 6GHz to 16GHz. York's group measured the output third-order intercept for the amplifier, and found that it was 52dBm. This compares with the third-order intercept of 38dBm for a single MMIC amplifier. This is a 14dB improvement in linearity, and it can be attributed to the fact that input power in the array is split between 32 amplifiers. The power saturation limit for the amplifier is proportional to the number of MMIC amplifiers in the array. We would predict a 15-dB improvement, which is close to the observed value. Mike DeLisio has also observed this improvement in mixer-diode grids at the University of Hawaii [17].

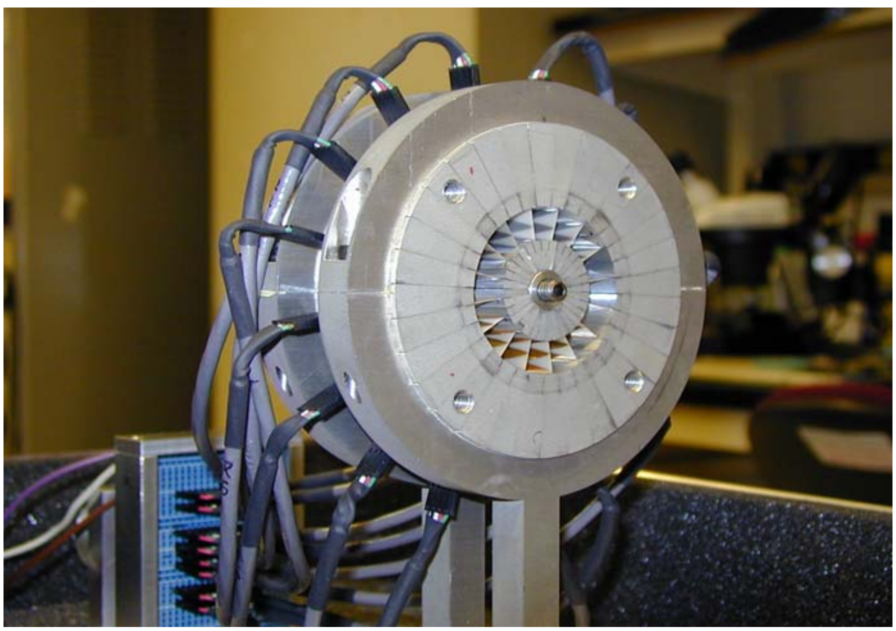


Figure 2. A 6−16 GHz broadband coaxial combiner with 32 MMIC amplifiers mounted on finline inside a coaxial waveguide [15]. The maximum output power was 50W, and the gain was better than 10dB over a 3:1 bandwidth.

High-Efficiency Class-E Amplifier Spatial Power Combining

Active quasi-optic transmitters are well-suited for high-power systems, because the output powers of large numbers of devices can be combined in free space. Thermal management is easier in some respects than in single-transistor amplifiers, because heat is generated uniformly over the array. Even so, the large powers that are involved make it critical to consider approaches that include efficient amplification. This is important in many other wireless applications also. The basic technique for achieving high-amplification efficiency in an amplifier is to use the amplifier primarily as a switch. As much of the cycle as possible, the transistor channel should be either non-conducting (*off*), or highly conducting (*on*). When

the channel is non-conducting the current is limited to capacitive currents which are inherently low-loss. When the channel is highly conducting, the channel voltage is small, and this limits the power absorbed the transistor. There is still loss associated with the transitions between the *on* and *off* states. Even though this is a small part of the cycle, the loss can be significant, because both the current and voltage can be large at the same time. The largest loss typically occurs when the transistor is switched *on*, because the drain capacitance discharges through the conducting channel. This accounts for most of the loss in digital computer circuits, and considerable loss in switching transmitter amplifiers. Typically 2/3 of the loss is associated with *on*-channel conductance and 1/3 of the loss is associated with the capacitive discharge. More than 20 years ago, Nathan Sokal recognized that the solution to the capacitive discharge problem was to use a load with somewhat inductive reactive designed to bring the *off* voltage back to zero when the transistor turns *on*. This eliminates the capacitive discharge loss, and allows extremely efficient amplification. Sokal called this amplifier a Class-E amplifier.

Even though these amplifiers are highly efficient, there are limitations in some communications and radar applications because these are not linear amplifiers. They can be used in systems with phase and frequency modulation. However, it more complicated circuits are required to use them with modulation schemes where the phase and amplitude vary in a complicated way [18].

Zoya Popovic's group at the University of Colorado has demonstrated a 16-element 10-GHz spatial combiner based on four 4-element spatial power combiner sub-arrays [19]. In the sub-array, the commercial GaAs-MESFET amplifiers are designed to operate in switched class-E mode, feeding dual-layer patch antennas. A Wilkinson combiner feed was designed for the input with 0.7 dB loss. The individual amplifiers operate at 64 % drain efficiency and deliver 20.6dBm output power. The total output power delivered from the active array is 26.6dBm (0.46W), for 20dBm input power. The average drain efficiency of the amplifiers in the array is 70% and the power added efficiency is 57%. The 4-sub-array 16-element combiner demonstrated an average drain efficiency of 70% at 164W EIRP, or about 1.4W of transmitted power. The power combining efficiency of the 16-element array is above 79%.

An oscillating antenna element at X-band was designed for high conversion efficiency and directivity. The element is suitable for integration into arrays due to simple biasing and compactness. A microstrip annular ring is used both as the radiating element and microstrip feedback circuit for the class-E amplifier. A maximum conversion efficiency of the dc power consumption to the radiated co-polarized power is measured to be 55% at 10GHz with a radiated power of 15.5dBm from a single low-cost Alpha AFM04P2 MESFET. The antenna gain is measured to be 8.1dB. When the correct mode is excited, the annular ring radiates as two surface current elements separated by half of a free-space wavelength in the E-plane. This enables a dense array lattice with low mutual coupling between elements. Since the active circuit is inside the ring antenna, the spacing in the array can be half wavelength in both directions. A paper describing details of this work was presented at the 2002 IEEE IMS. Continuing work in this area is in the direction of a high-efficiency DC-DC converter at a 10-GHz switching rate [20].

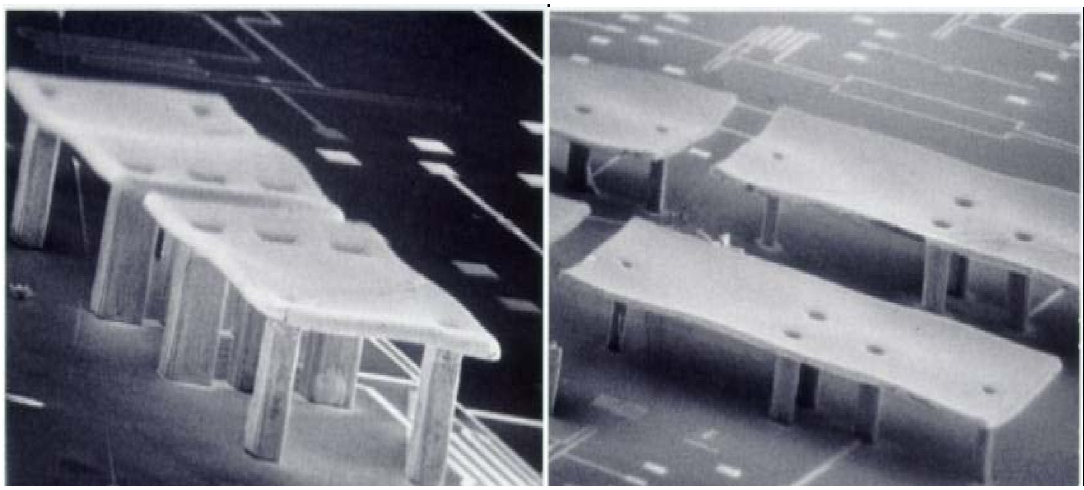
Broadband arbitrarily-polarized rectenna arrays for recycling low incident power levels

This is a new topic that was not addressed in the original proposal, but we believe fits well in the area of quasi-optic power combining. Professor Popovic has been investigating it at the University of Colorado. One can classify spatial power combiners according to power input and output as follows: (1) DC power is the input and RF power is the output (oscillators); (2) RF power in a wave is the input and output (amplifiers and multipliers); and (3) RF power in an incident wave is the input and DC power is the output (rectennas). Under this MURI, the University of Colorado group has demonstrated high-efficiency oscillator antennas, high-efficiency PA combiners, high conversion efficiency multipliers, and in this last year we have focused a part of the effort on rectennas [21].

Most rectennas have been developed for energy beaming using linearly (or otherwise well-determined) antennas with high-power incident radiation for high efficiency of rectification. We address another application – that of recycling RF energy that is incoherently scattered over a large spectral bandwidth with low power at any individual frequency. Since the polarization is randomly varying in time, the rectenna design is such that two orthogonal polarizations are rectified independently and the resulting DC voltages and/or currents are added. Rectification for single-frequency sources from 4 to 14GHz with a single array has been demonstrated. The efficiency is a function of incident power, as expected, and can reach values of over 65% for FCC-allowed power densities. Zoya Popovic's group has demonstrated non-linear increase in efficiency and DC power as multi-spectral waves are incident on the rectenna array.

W-Band MEMS Antennas

We have developed MEMS-based metal dipole and gamma-matched antennas for a 94-GHz quasi-optical array. The antennas are designed and modeled at Caltech and fabricated by Mark Rodwell's group at UCSB. Prototypes are shown in Figure 3. The fabrication process was quite difficult and it involved repeated plating and photoresist patterns. The MURI work at UCSB used transferred-substrate HBTs, a device structure which provided high *fmax* but whose process made integration with MEMS antennas very difficult. However, the resulting metal structures were 0.15 mm high. The advantage of building all-metal antennas in this fashion is that dielectric absorption losses are eliminated and there is no coupling to a dielectric substrate. We do not have pattern measurements for these antennas. However, HFSS simulations indicate that both antennas have a 7% 2:1 SWR bandwidth. The predicted metal losses for the dipole antenna are 0.4dB, while the predicted metal losses for the gamma-matched antenna are somewhat higher, 2.1dB. Even thought the losses for the dipole antenna are lower than for the gamma-matched antenna, the dipole antenna is a balanced structure, and it would require a balun with additional complexity and losses to drive it.



(a) (b)

Figure 3. (a) Dipole antenna side view (w = 0.31mm, l = 0.4mm, h = 0.15mm). (b) Gamma-matched antenna side view (w = 0.7mm, l = 1.1mm, h = 0.15mm).

Millimeter-Wave Power HBTs

Mark Rodwell's group at the University of California at Santa Barbara is developing high power W-band amplifier arrays in InP HBT technology. Results on the program have progressed through demonstration of transistors with very high power capability W-band and of demonstration of HBT amplifiers with record output power levels in W-band.

As a key step, in the MURI program, HBTs with large power-handling capabilities were developed. This required adding additional metal layers to the base contact structure so as to decrease the sheet resistivity, as this otherwise contributes substantially to the base access resistance of power transistors with large junction areas. Greatly increased thermal stability was also required, and was accomplished in part through the standard addition of external ballast resistances for each individual emitter finger. This prevents thermal instability in the distribution of current between the multiple emitter fingers of the power transistors. Additionally, transistors were developed with a lightly doped emitter layer added to the transistor layer structure itself. This layer increases the access resistance per unit emitter junction area and prevents thermal instability in the distribution of current within an individual emitter finger.

Large-junction-area InP DHBTs were designed and fabricated using transferred-substrate technology and exhibited fmax of 330GHz when measured at 100mA collector bias current and 3.6V collector-emitter bias voltage. Devices with the lightly doped emitter layer were designed and fabricated; these demonstrate 235 GHz fmax when biased at 140mA current and 3.7V collector-emitter bias voltage. The latter devices are thermally stable at twice this current, 280 mA, when biased at low Vce, while the low-current breakdown voltage exceeds 8 volts. The theoretical maximum unsaturated output power is therefore 245 mW. DHBT millimeter-wave power amplifiers were then designed, fabricated, and tested. Reactively matched common-base amplifier MMICs, with 8.5 dB insertion gain at 85 GHz, delivered saturated output power of 16.6 dBm. A cascode amplifier demonstrated an insertion gain of 8.6 dB and saturated output power of 12.5 dBm at 90 GHz. Other reactively matched common-base amplifiers with the lightly doped emitter layer structure demonstrated 80 mW

saturated output power at 75GHz. These power levels are record for HBTs. It should be note that much higher-power designs (up to 250 mW) were attempted but did not succeed due to IC process limitations; the higher-power devices have large numbers of transistor junctions connected in parallel.

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